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EVALUATION OF TANGENTIAL VELOCITY EFFECTS ON SPINNING TRANSVERSE COMBUSTION INSTABILITY

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SUMMARY

An evaluation is made of the effect of a steady tangential or vortex flow on traveling transverse mode instability in rocket combustors. Experimental and analytical evidence of changes in stability limits caused by tangential flow is presented. Relatively low magnitude flows (a few feet per second) are found to affect stability substantially. This sensitivity is shown to be consistent with the effect of a steady tangential velocity on the dynamic response of a velocity sensitive mechanism such as propellant atomization or drop vaporization. The probability of incurring such velocities in developmental combustors is examined. A small tangential velocity can result from several causes. Its detection, however, can readily be obscured by other flow processes. Steady tangential velocities in the direction of the wave motion and opposed to the motion are shown to have inverse effects on the energy released in phase with the pressure oscillations which, in turn, may amplify or damp, respectively, the acoustic oscillations. It is concluded that this characteristic of tangential flow may be useful in the control of combustion instability in rocket combustors.

INTRODUCTION

The search for methods and techniques for suppression or elimination of combustion instability in rocket engines will be a continuing effort until satisfactory solutions are attained. In the pursuit of this goal, many of the parameters known to affect the stability of a combustion system have been extensively investigated. Acoustic liners, chamber baffles, drop and jet breakup times, axial energy release, and combustor geometry have received extensive study, and a significant improvement in controlling and predicting instability has resulted. Additional improvement, however, is required. Thus a need exists to continue these efforts as well as to explore other factors previously not considered.

Recent experimental and theoretical studies have shown that a steady tangential or vortex velocity causes substantial changes in the stability boundaries associated with traveling transverse oscillations. The purpose of this report is to discuss the heretofore neglected significance of these angular flow effects to the problem of combustion instability in developmental combustors. Available information on stability boundaries is presented and discussed to illustrate the sensitivity of instability to tangential velocity. An analysis of velocity dependent mechanisms is presented which accounts for this sensitivity. Finally, the contribution of tangential velocity effects to the cause of instability and the utilization of such velocities in the elimination of instability are discussed. The discussion is qualitative in its application to instability in developmental combustors, but it demonstrates the probable value of additional experimental and theoretical studies.

SYMBOLS

$\mathscr{A}$	contraction ratio, dimensionless
a	speed of sound, ft/sec
E	instantaneous energy release, (ft)(lb)/sec
$\overline{E}$	average energy release, $\overline{E} = \frac{1}{2\pi}\int_0^{2\pi} E\,dt$, (ft)(lb)/cycle
$\tilde{E}$	average of oscillating component of E in phase with pressure, $\tilde{E} = \frac{1}{2\pi}\left[\sum_{-\pi/2}^{\pi/2}(\overline{E} - E) + \sum_{\pi/2}^{3\pi/2}(E - \overline{E})\right]$, (ft)(lb)/cycle
J_1	Bessel function, first kind, first order
$\mathscr{L}$	burning rate parameter, $Rm/\mathscr{A}$, dimensionless
M_x	Mach number based on ΔV_x
M_θ	Mach number based on ΔV_θ
$M_{g,x}$	Mach number of axial velocity component of gas
$M_{g,\theta}$	Mach number of tangential velocity component of gas
$\mathscr{M}_L$	mass concentration of unvaporized propellant, lb/cu in.

m fraction of propellant burned per inch, $in.^{-1}$

O/F oxidant-fuel weight ratio, dimensionless

P_c chamber pressure, lb/sq in.

ΔP_c chamber pressure oscillation amplitude, peak-to-peak, lb/sq in.

R combustor radius, in. or ft

t time, sec

ΔV net velocity difference between liquid and gas, $\Delta V = (\Delta V_x^2 + \Delta V_\theta^2)^{1/2}$, ft/sec

ΔV_x velocity difference between liquid and gas, axial direction, ft/sec

ΔV_θ velocity difference between liquid and gas, tangential direction, ft/sec

W_{atom} atomization rate, lb/(sec)(cu in.)

W_{vap} vaporization rate, lb/(sec)(cu in.)

β chamber radius, $\omega R/a$, dimensionless

γ specific heat ratio, dimensionless

ϵ oscillation amplitude, dimensionless

θ angular position, rad

ρ gas density, lb/cu in.

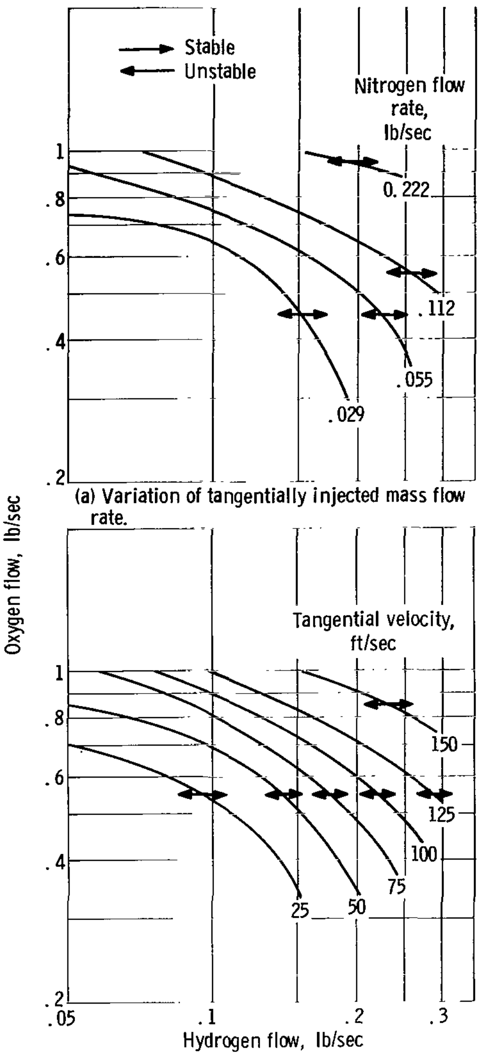
ω frequency, rad/sec

Superscript:

— average value

EXPERIMENTAL COMBUSTION STUDIES WITH TANGENTIAL VELOCITY

Several studies have been made with both liquid and solid propellant combustors in which transverse oscillations were induced by a tangential flow velocity (refs. 1 to 4). This effect has been examined in some detail in a two-dimensional circular liquid propellant combustor (refs. 1 and 4). In this particular combustor, the injection of a tangential flow of nitrogen gas produced pressure oscillations that were identified as the first transverse traveling mode of the combustor. The nitrogen flow rate required to cause instability was determined for a range of combustor operating conditions (P_c, 100 to 300 lb/sq in.; O/F, 2 to 10). Typical results in the form of stability boundaries are shown in figure 1(a) for various nitrogen mass flow rates. In the absence of nitrogen flow, this combustor was stable. As shown in figure 1(a), increasing the nitrogen mass flow rate expanded the region of unstable operation.



(a) Variation of tangentially injected mass flow rate.

(b) Variation of tangential velocity.

Figure 1. - Stability boundaries in two-dimensional circular combustor.

From a knowledge of the injection rates, it is possible to calculate the tangential gas velocity at the circumference of the combustor by using the momentum balance given in reference 1. Figure 1(b) shows the stability boundaries as a function of the tangential gas velocity. The unstable region is quite sensitive to tangential velocities of relatively small magnitude.

Figure 2 shows the effect of tangential velocity on the measured pressure amplitude $\Delta P_c/P_c$ for this combustor at oxygen and hydrogen flow rates of about 0.4 and 0.15 pound per second, respectively. A threshold velocity for instability of about 30 feet per second was observed at this condition. Initially, pressure amplitude increased almost linearly with velocity. At higher velocities the amplitude asymptotically approached a value of about 90 percent. The significance of these results is that the pressure amplitude can be increased or decreased by varying the tangential gas velocity.

Other techniques of inducing transverse oscillations include the use of tangentially alined shock tubes and explosive devices. In each of these techniques, the pressure pulse generated by the device is accompanied by a tangential flow of gas. The relative contributions of the pressure pulse and the gas velocity toward initiating oscillations remain unresolved.

THEORETICAL COMBUSTION STUDIES WITH TANGENTIAL VELOCITY

The effect of a steady vortex velocity on stability boundaries in a toroidal combustor has been calculated in reference 5 for a vaporization-limited combustion model. The results taken from reference 5 are shown in figure 3. For small pressure disturbances, the stability limit is extremely sensitive to a small steady vortex or tangential velocity. Conversely, given a small vortex velocity, the curves predict that essentially infinitesimal disturbances will grow. The vortex velocities (based on a speed of sound of 5000 ft/sec) required to trigger instability ranged from about 15 feet per second at a value of

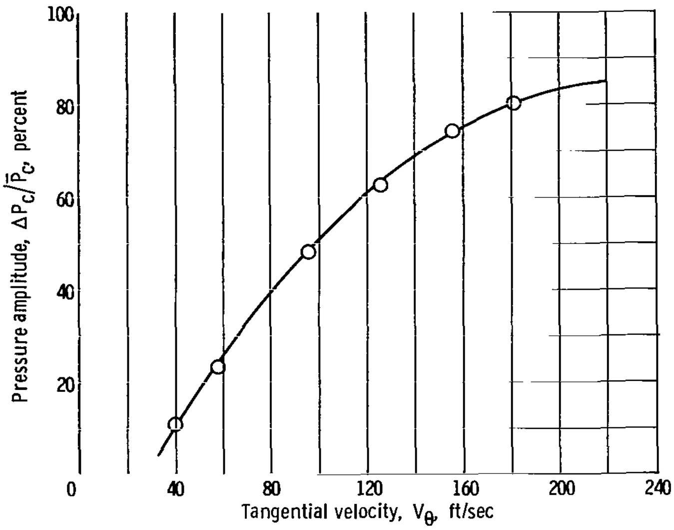


Figure 2. - Effect of tangential velocity on pressure amplitude of combustion instability in circular combustor (ref. 4). Oxygen flow rate, 0.4 pounds per second; hydrogen flow rate, 0.15 pounds per second.

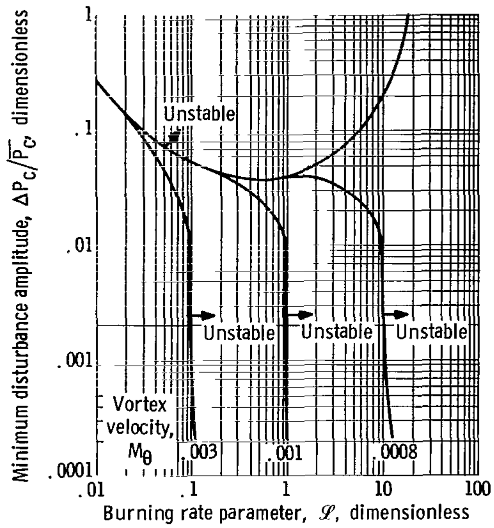


Figure 3. - Effect of vortex velocity on stability boundaries calculated for vaporization-limited model of toroidal combustor (ref. 5).

0.1 for the burning rate parameter $\mathscr{S}$ to about 4 feet per second at a value of 10. Interestingly enough, if $\mathscr{S}$ is large for a given geometry, indicating that the combustion is more concentrated spatially, a smaller vortex velocity is required to induce instability.

In order to compare the experiments of reference 4 with the theory, an $\mathscr{S}$ value for the experimental combustor must be approximated. Since the combustor was not 100 percent efficient (ref. 4), it can be assumed that the entire radius (equivalent to length in a cylindrical combustor) was needed for the burning process. The simplest assumption is that the fraction of propellant burned per inch m varied linearly with radius and was 0.25. Contraction ratio for this combustor geometry is probably most logically defined (ref. 5) as the volume of the combustor divided by the product of nozzle area and the distance from injector to nozzle (i.e., combustor radius). As defined, the contraction ratio $\mathscr{A}$ was 8. These values of m and $\mathscr{A}$ result in an $\mathscr{S}$ of 0.125. According to figure 4, the stability boundary at this value of $\mathscr{S}$ occurs at a vortex velocity of about 15 feet per second for small pressure disturbances. The experimental value found was about 30 feet per second. Thus, from both experimental and theoretical evidence, the stability limits of a combustor to traveling transverse oscillations are apparently sensitive to a steady tangential velocity. In the following discussion, an attempt will be made to develop a simple model and explanation for this sensitivity and to suggest the use of tangential velocity as a possible means for controlling this mode of instability.

TANGENTIAL VELOCITY AND COMBUSTION MECHANISMS

The foregoing discussion has shown experimental and theoretical evidence that a low

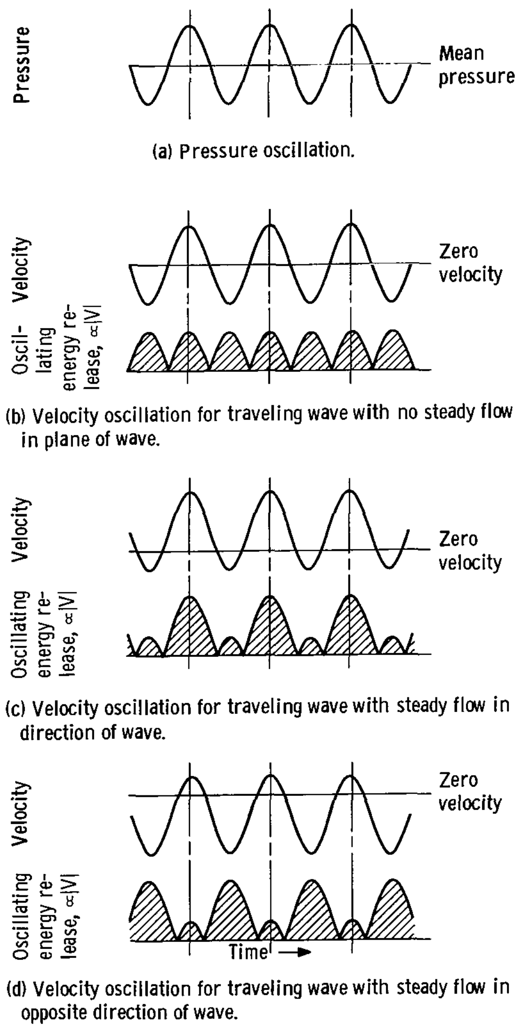


Figure 4. - Phase relations for spinning transverse waves.

steady tangential velocity can readily excite the traveling transverse mode of combustion oscillations. To explain this effect, a simple model of a quasi-steady velocity-dependent combustion mechanism incorporating the effect of this velocity will be developed. It is assumed that the energy released from the combustion process depends on the value of the absolute velocity. Figures 4(a) and (b) show the variations of pressure and velocity with time, respectively, for a traveling transverse wave without a steady velocity component. If the energy release is linearly related to the absolute velocity, the energy release curve shown in figure 4(b) results. It can be seen that the energy release is symmetric and reaches a maximum twice during each cycle of the pressure wave. Thus, no energy is added preferentially to either drive or damp the wave, and the system can be considered to be neutrally stable according to Rayleigh's criterion (ref. 6). Such velocity coupling effects have been discussed for axial mode instability in solid propellant engines (ref. 7) and for transverse instability in liquid propellant engines (ref. 8).

If a time-independent velocity, or steady velocity, is superimposed on the oscillating velocity as shown in figure 4(c), the in-phase energy release increases at the expense of the out-of-phase energy release. The wave thus is driven by biasing the velocity in the direction of wave motion.

Biasing the velocity in the direction opposite to the wave motion gives the results shown in figure 4(d). In this case there is a net increase in the out-of-phase energy release, and the wave is damped.

At least two processes associated with the combustion of liquid propellants show dependence on velocity although not in the simple linear manner of the preceding discussion: droplet vaporization and atomization. As given in reference 5, the rates of these two processes are

$$W_{vap} \propto \left(\rho \left| \Delta V \right|\right)^{1/2}$$

and

$$W_{atom} \propto \rho^{5/12} |\Delta V|^{1.25}$$

For the vaporization process the net fractional energy addition (or loss) to the wave over a cycle was calculated. It was assumed that the energy release was directly proportional to the evaporation rate. The results are shown in figure 5 where the ratio of net energy exchange $\tilde{E}$ to the average energy $\overline{E}$ is plotted for relative tangential velocity up to a Mach number $\overline{M}_\theta$ of 0.1. The axial Mach number $\overline{M}_x$ was 0.02. The inviscid solutions given by reference 9 for the first traveling transverse mode were used to describe the gas properties and flow:

$$\frac{P_c}{\overline{P}_c} = 1 - \epsilon\gamma J_1(\beta)\cos(\omega t + \theta)$$

$$\frac{\rho}{\overline{\rho}} = 1 - \epsilon J_1(\beta)\cos(\omega t + \theta)$$

$$M_{g,\theta} = \overline{M}_{g,\theta} + \frac{\epsilon J_1(\beta)}{\beta}\cos(\omega t + \theta)$$

The extent of driving or damping was determined by comparing the energy-release time variation given by $(\rho|\Delta V|)^{1/2}$ with the pressure time variation and by computing the net of the in-phase energy addition or the out-of-phase energy loss. As shown in

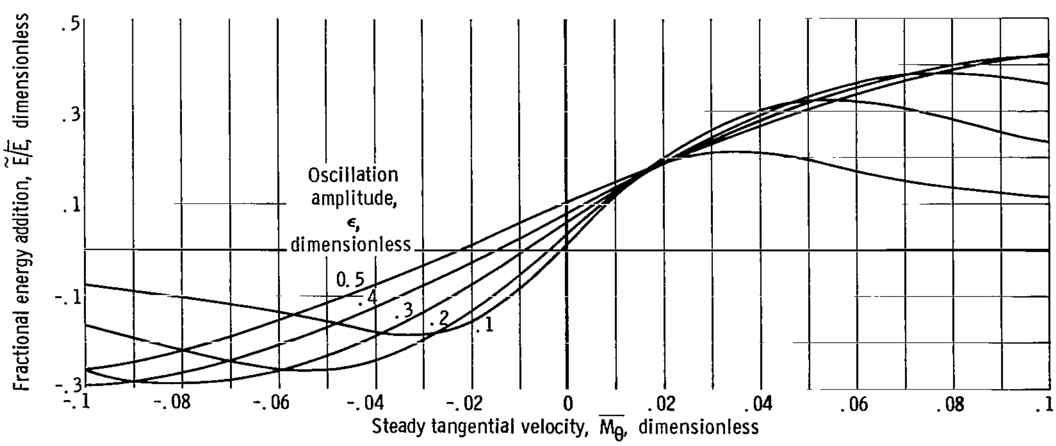


Figure 5. - Effect of tangential velocity on the phase-related energy release. Calculated for vaporization-limited model in toroidal combustor (ref. 5). Axial Mach number, $\overline{M}_x$, 0.02.

figure 5, the energy release indicates that driving occurs with no bias velocity. In this case, the effect is due solely to density, since, in the linear example shown in figure 4, an unbiased velocity was the neutral condition. Starting from this point, increasing the bias velocity either serves to drive the wave or damp the wave dependent on whether it follows or opposes the wave motion, respectively. Once the velocity is completely biased at a given wave amplitude, the ratio $\tilde{E}/\overline{E}$ decreases and approaches zero asymptotically because further increases in the bias velocity serve only to increase the average energy portion rather than the oscillating portion. In this case, the oscillating portion can be increased only by increasing the wave amplitude. The effect of increasing the steady axial flow $\overline{\Delta V_x}$ is also to decrease the ratio $\tilde{E}/\overline{E}$, since it contributes only to the average energy of the system. Thus, the largest values of $\tilde{E}/\overline{E}$ occur when the $\overline{\Delta V_x}$ is at or near zero. This aspect has been brought out in discussions in references 10 and 11 where it was pointed out that the most sensitive interval in the course of combustion occurs when the velocity difference (between the gas and a drop) passes through zero.

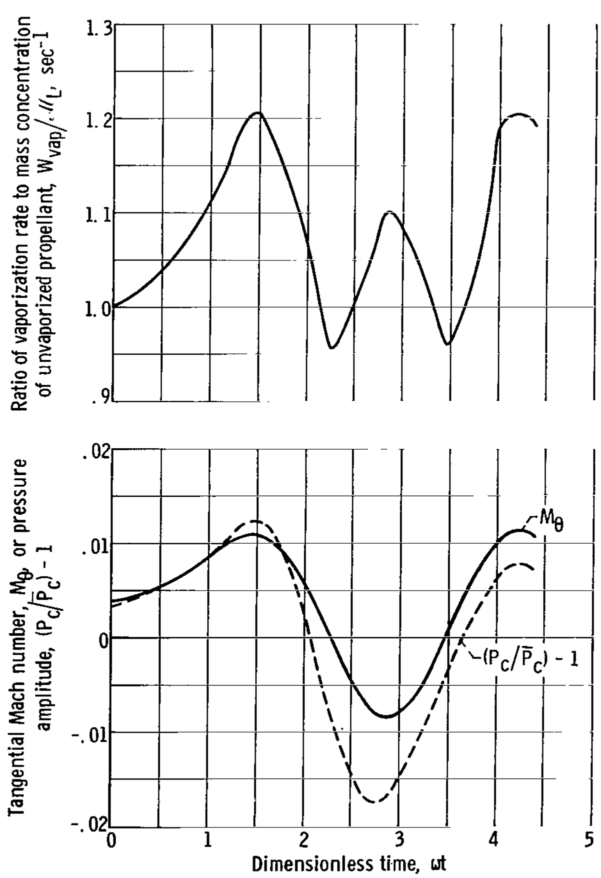


Figure 6. - Phase relations from vaporization model with initial vortex velocity. One-dimensional toroidal combustor. Input conditions: burning rate parameter, $\mathscr{L}$, 0.1; tangential Mach number, M_θ, 0.004; pressure amplitude, $\Delta P_c/P_c$, 0.01; Mach number of axial velocity component of gas, $M_{g,x}$, 0.05.

Some of these effects can be observed in the more complex analysis of reference 5 where the feedback from the combustion process to the pressure wave was included. Figure 6 shows the pressure, velocity, and vaporization rate histories for an unstable condition in a vaporization-limited process. For convenience, $(P_c/\overline{P}_c) - 1$ has been plotted in figures 6 and 7. The pressure and velocity are seen to be essentially in phase as occurs in a traveling wave. A frequency doubling in the vaporization rate curve was also observed in response to the velocity-sensitivity of this process.

In view of the extremely small tangential velocity needed to induce instability in these calculations (ref. 5), some other calculated data similar to that of reference 5 were examined to see if a steady tangential velocity component appeared when it was not included in the initial conditions of the calculation. These

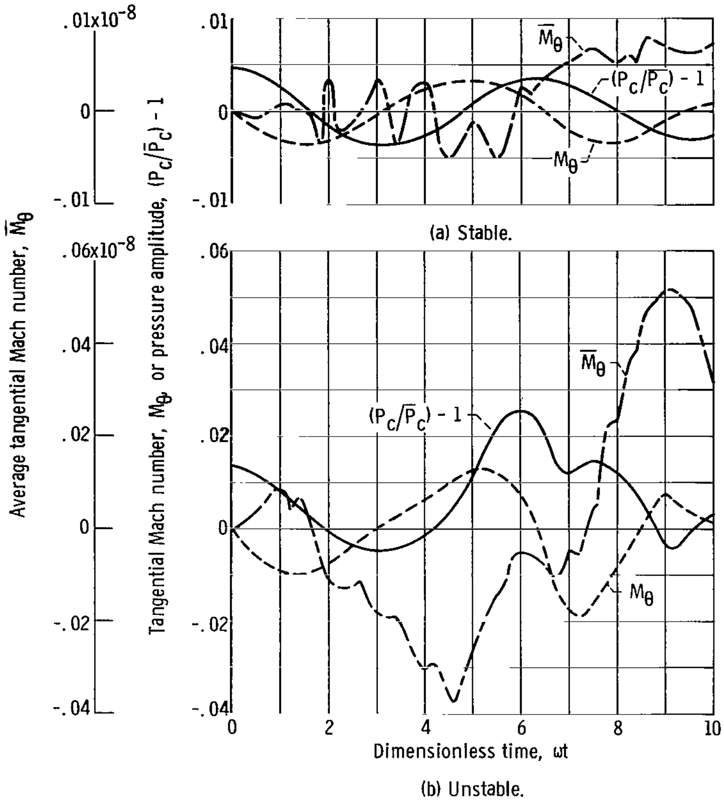


Figure 7. - Calculated pressure-velocity time histories with vaporization-limited model in two-dimensional annular combustor. Initial vortex velocity not included; angular position, $\theta = \pi/4$ radians.

data are shown in figures 7(a) and (b) for a stable and an unstable case, respectively. In the stable case (fig. 7(a)) the pressure and velocity are phase related as in a standing wave when compared at the same angular position. The tangential velocity component, averaged with respect to angular position, was quite small and had only a random time variation, which somewhat resembles turbulent fluctuations. In the unstable case (fig. 7(b)) pressure and tangential velocity were initially in a standing wave relation but tended to progress into a traveling wave phase relation. In this case, the net tangential velocity component, while still very small, was nonzero and appeared to have a frequency about one-fourth that of the pressure wave. The vaporization rate curves for both these cases did not show any tendency toward frequency doubling as was found in figure 6. The contribution from tangential velocity is probably obscured because of its smallness ($M_\theta \cong 0.01$) as compared with the axial velocity ($\bar{M}_x \cong 0.1$). These calculations do not establish tangential velocity as a cause of instability; however, they do indicate that a traveling wave may result from the nonlinear treatment of a standing wave and that a net tangential velocity may occur during instability.

TANGENTIAL VELOCITY AND DEVELOPMENTAL COMBUSTORS

The significance of tangential velocity in developmental combustors can be considered from two standpoints: as the cause of unstable combustion in existing engines, or as a means of controlling instability in these engines. These two views will be discussed separately.

Source of Instability

Some evidence for tangential velocity components in full-scale engines does exist. For example, a large roll disturbance in the third stage of the NASA Scout ST-1 vehicle was found to coincide with large amplitude chamber pressure vibrations (ref. 12). These vibrations were tentatively identified as tangential modes of instability. At high amplitudes, such oscillations are accompanied by acoustic streaming flows, as found in reference 9. These effects have been discussed also in references 3 and 13. The present discussion is concerned with small tangential velocities that may initiate instability and thus occur prior to, or simultaneously with, pressure oscillations.

Tangential velocity during stable combustion in developmental combustors has not been reported to date. The detection, however, might be more difficult than casual observation indicates. This detection difficulty is illustrated in figure 8, which shows the helix angle of an axial streamline as a function of tangential velocity and combustor contraction ratio. The helix angle, calculated by considering only steady axial and tangential velocities, is large (essentially axial flow) for low contraction ratio engines. An 89° angle is indicated for a 1.5 contraction ratio engine with a tangential velocity of 40 feet per second. Such a velocity is more than sufficient to cause instability for values of $\mathscr{L} > 0.1$ according to figure 3 (p. 5). The detection of such a velocity would be difficult. All that can be concluded is that evidence does not preclude the presence of low tangential velocities in developmental combustors.

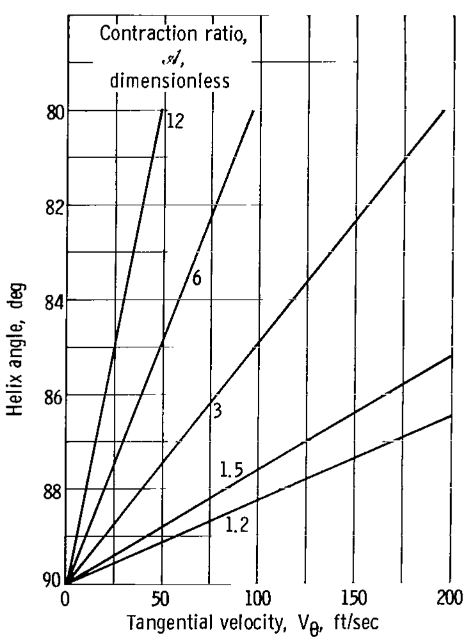


Figure 8. - Helix angle of ideal gas flow vector as function of tangential velocity for several contraction ratios. Speed of sound, a, 5500 feet per second.

Vortex generation in flowing media is frequently encountered. A variety of pressure distributions due to obstructions such as baffles or injector contours can promote tangential or vortex velocity.

Another source is the angular momentum imparted by injected propellants since injection from individual elements is not necessarily in the axial direction.

Experimentally, the wave direction in spinning transverse oscillations was found to occur in a preferred direction dependent on the orientation of injector elements (ref. 8). This preferred direction was attributed to the enhanced burning rate that would occur if the wave induced a variation in the mixture ratio in the vicinity of the injection point. As an alternative view it can also be postulated that during combustion adjacent oxidant and fuel injection points (due to blocking of one by the other) give rise to a lateral flow of gases that is predominantly directional. Under such conditions the tangential flow would promote instability in this preferred direction.

Tangential velocity may be the cause of instability in developmental combustion, and consideration should be given to this possibility in designing combustors.

Control of Instability

In principle, the foregoing discussion suggests a means of controlling transverse spinning combustion instability. The requirements are a controllable tangential velocity and a means of determining the propagation direction and the magnitude of the wave. Upon detection of a spinning oscillation, a tangential velocity opposite in direction to the wave would be initiated and the energy release of this combustion process would then cause the wave to damp. The tangential velocity would be reduced as the wave decayed and reversed in direction if a wave in the opposite direction developed. In principle, such a scheme, although undeveloped, would provide positive stabilization of the combustor.

Ideally, the propellants to be burned should be used as a source of the tangential velocity. For example, one could inject the propellant in a manner so that its vector direction may be changed or one could inject a part of the propellant tangentially. Other methods such as variable angle control vanes, or baffles, secondary flow injection, combustion gas by-pass, and other techniques might prove more advantageous in certain applications. Achieving stability by controlling tangential flow would avoid the ordinary methods of stabilization, such as injector changes and baffle installations, that are presently employed and are unique to each combustor.

CONCLUDING REMARKS

This discussion of the tangential velocity effects on spinning transverse combustion instability has shown that tangential velocity is significant to the problem of combustion instability in developmental combustors. Its importance should be emphasized in the design and testing of combustors so that this source of instability can be eliminated. The use of tangential velocity as a means of controlling instability obviously requires considerable developmental effort before it can become applicable. It would only be effective for oscillatory combustion processes which are sustained by velocity sensitive combustion mechanisms. That control may be effective in one combustor and not in another is also probable.

The velocity sensitive mechanism proposed and its extreme sensitivity to small tangential velocities suggest that these may be principal causes of combustion instability. In the case of transverse instability, they further suggest that the success of baffles may be due to their preventing these tangential velocities from occurring.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 26, 1966.

REFERENCES

1. Heidmann, Marcus F.: Oscillatory Combustion of a Liquid-Oxygen Jet with Gaseous Hydrogen. NASA TN D-2753, 1965.

2. Povinelli, Louis A.; and Heidmann, Marcus F.: Study of Transverse Mode Solid-Propellant Combustion Instability. Vol. 1 of Proceedings of the 1st ICRPG Combustion Instability Conference, CPIA Publ., No. 68 (DDC No. AD-458060), Johns Hopkins University, Jan. 1965, pp. 409-412.

3. Swithenbank, J.; and Sotter, G.: Vortex Generation in Solid Propellant Rockets. AIAA J., vol. 2, no. 7, July 1964, pp. 1297-1302.

4. Heidmann, Marcus F.: Oxygen-Jet Behavior During Combustion Instability in a Two-Dimensional Combustor. NASA TN D-2725, 1965.

5. Priem, Richard J.: Influence of Combustion Process on Stability. NASA TN D-2957, 1965.

6. Rayleigh, John W.S.: The Theory of Sound. Vol. II, 2nd ed., Dover Publications, 1945, p. 226.

7. Price, E.W.: Axial Mode, Intermediate Frequency Combustion Instability in Solid Propellant Rocket Motors. Preprint No. 64-146, AIAA, Jan. 1964.

8. Reardon, F.H.; Crocco, L.; and Harrje, D.T.: Velocity Effects in Transverse Mode Liquid Propellant Rocket Combustion Instability. AIAA J., vol. 2, no. 9, Sept. 1964, pp. 1631-1641.

9. Maslen, Stephen H.; and Moore, Franklin K.: On Strong Transverse Waves Without Shocks in a Circular Cylinder. J. Aeron. Sci., vol. 23, no. 6, June 1956, pp. 583-593.

10. Beltran, M.R.; and Frankel, N.A.: Prediction of Instability Zones in Liquid Rocket Engines. AIAA J., vol. 3, no. 3, March 1965, pp. 516-518.

11. Levine, R.S.: Experimental Status of High Frequency Liquid Rocket Combustion Instability. 10th Symposium (International) on Combustion, Combustion Institute (Pittsburgh, Pa.), 1965, pp. 1083-1099.

12. Mayhue, Robert J.: NASA Scout ST-1 Flight-Test Results and Analyses, Launch Operations, and Test Vehicle Description. NASA TN D-1240, 1962.

13. Flandro, G.A.: Roll Torque and Normal Force Generation in Acoustically Unstable Rocket Motors. AIAA J., vol. 2, no. 7, July 1964, pp. 1303-1306.

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